HEWLETT-PACKARD CORPORATION VI (A)

Signal Generator Read-out Design

A Read-out Device Problem

"Shrinking an 8" dial into an area less than a tenth that size without sacrificing readability is not a new problem. Several companies I know have invested in R and D like this before, but the answers they came up with weren't suited to our needs. They were either too big or too expensive or too inaccurate"

This was the comment of Tony Badger, a mechanical engineer at Hewlett-Packard. The dial he was talking about was to be a read-out device (similar to the station indicators found on radios) for a high frequency signal generator which he and his group were developing. One of the problems he faced was to design this read-out device to fit on the front of what turned out to be a very small signal generator.

Readout examples can be seen in Appendix A.

Prepared by Robert Beardmore and Charles Fernald in the Engineering Casewriting Course of Stanford University conducted by Karl H. Vesper. Printed with support from the National Science Foundation. The cooperation of Mr. Anthony Badger, Mr. Peter Rich and the Hewlett-Packard Company in making this material available is gratefully acknowledged.

"I not only got the O.K., but the project was given to me 'free-field', that is, it was independent research. I defined what I wanted, (a simple, temperature insensitive, mechanically variable capacitor and inductor).* I stayed entirely away from what I thought caused the modulation and calibration difficulties, and came up with some elements which looked pretty promising. This was in April of 1966."

"At this point, the project refined itself. To use these elements in a signal generator, I had to find some way to drive** them, design the basic circuitry around them and come up with a small enough read-out device. Management thought these elements had a lot of potential and decided to go ahead with the project. Some electrical engineers were assigned to the group and we began the design of the signal generator proper."

Tony stated that before he could begin design of the read-out, he had to have some idea of what the overall signal generator package might look like. Into how small a space would the read-out have to fit? "We weren't locked up on dimensions yet but the module concept suggested itself from the very first." A module is a circuit package, an individual little box into which components are fitted. Generally, the components are related to one particular function, for example, all the power supply components might be packaged together, or all the components related to a specific frequency range. The boxes may then be mounted together and inter-connected electrically by plugs or jacks.

Tony felt that modules offered the best return on an engineering investment. The same power supply module could be used with perhaps five different instruments without changing its circuitry. Thus the power supply has to be designed only once, not five times. In addition, by adding or subtracting modules, the customer can get the instrument he wants, buying neither more nor less than he actually needs.

Electronic test equipment is generally either mounted in racks or just set on a bench. Rack panels (see illustration on following page) are a standard width of 16" and start at 3" in height with 1-1/2" increments up to almost any size desired. Bench space is more critical in width than height since one can't always stack one piece of equipment on top of another. Tony continued, "and when you're finished arranging equipment on your bench, you still need room for your soldering gun, right? The module is an obvious solution to this problem since it allows different equipment arrangements." Modules may be mounted side by side for rack use or on top of one another for bench use.

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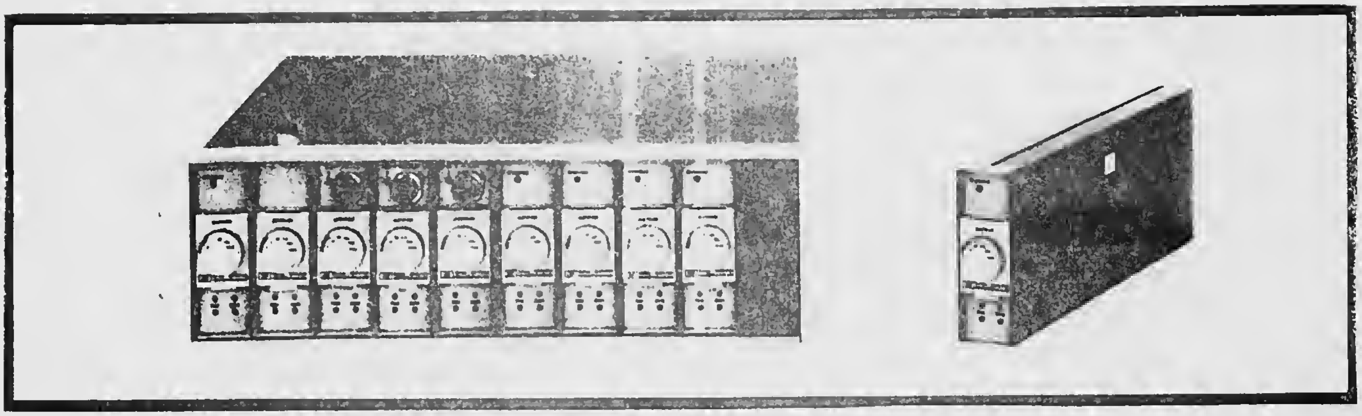
* See Appendix C.

**These elements are variable capacitors and inductors. Their values are changed (they are driven) by rotating a precision barrel cam. (Appendix C.)

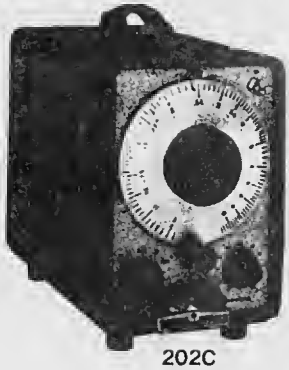


Typical modules, in this case, part of a differential amplifier, arranged here to that they may be mounted in a rack.

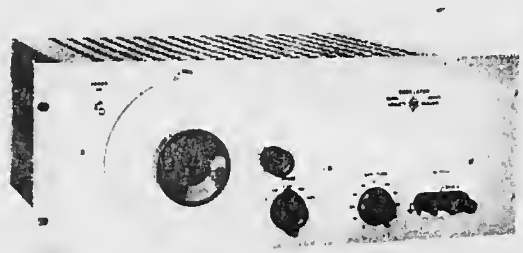
Using transistors, integrated circuits, and the tuning elements Tony came up with, H.P. electrical engineers combined the functions of three of the present model signal generators into one new model. This new model will be smaller by one half than any one of the present models. (See following illustration for pictures and dimensions of three present models.) This would represent a saving of about seven cubic feet and close to 150 pounds. Tony wanted to package the new signal generator in four separate modules, one for the power supply, attenuators, and amplitude modulators, and each of the other three for a specific frequency range. Each of these three modules needed its own read-out and one control for varying frequency within its range.

Individual Calibration

Signal generators are usually designed to supply a specific range of frequencies, say as an example, of from O(DC) to 20,000cps. The generator is adjusted to the desired frequency (for example to 18,250 cps) by turning a dial or control on the front. The generator must produce this signal within a certain accuracy.



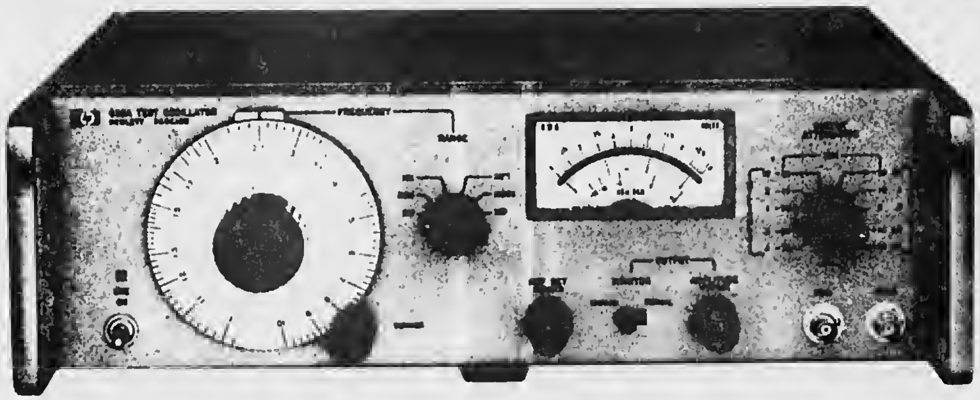
202C



200SR

LOW FREQUENCY SIGNAL GENERATOR

BENCH MODEL RACK-MOUNT MODEL



652A

MODEL DESIGNED FOR BOTH USES

8925A

SMALL RACK-MOUNT PANEL

The Three Signal Generators Being Replaced by the Single New Unit

Specifications

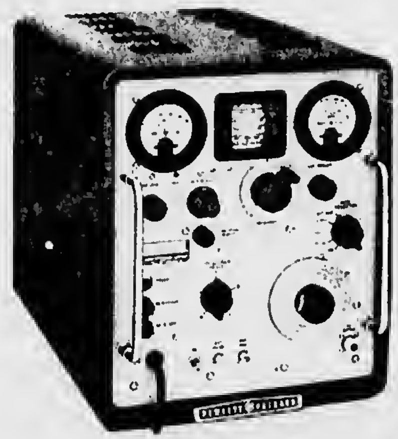
Frequency range: 450 to 1230 MHz in one band; scale length approximately 15" (381 mm).

Calibration accuracy: within ±1%; resettability better than 5 MHz at high frequencies.

Power: 115 or 230 volts ±10%, 50 to 400 Hz, 215 watts.

Dimensions: cabinet: 13½" wide, 16½" high, 21½" deep (343 x 419 x 546 mm); rack mount: 19" wide, 13-31/32" high, 20¼" deep behind panel (483 x 355 x 514 mm).

Weight: net 56 lbs (25,4 kg), shipping 68 lbs (30,5 kg) (cabinet); net 56 lbs (25,4 kg), shipping 72 lbs (32,4 kg) (rack mount).



608C

Major specifications, 608C,D

Frequency range: 608C, 10 to 480 MHz in 5 bands; 608D, 10 to 420 MHz in 5 bands.

Frequency dial calibration accuracy: 608C, ±1%; 608D, ±0.5%.

General:

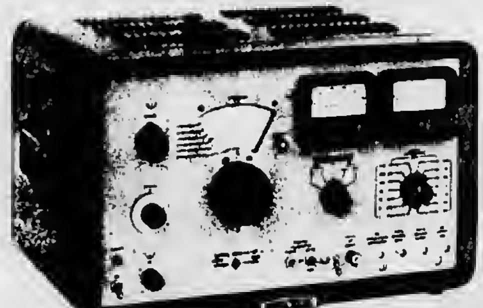
Power: 115 or 230 volts ±10%, 50 to 400 Hz; approximately 220 watts.

Dimensions: cabinet: 13¼" wide, 16⅜" high, 21" deep (337 x 416 x 533 mm); rack mount: 19" wide, 13-31/32" high, 18⅜" deep behind panel (483 x 335 x 467 mm).

Weight:

Cabinet mount: net, 62 lbs (28 kg); shipping, 73 lbs (33 kg).

Rack mount: net, 62 lbs (28 kg); shipping, 89 lbs (40 kg).



606B

Specifications, 606B

Frequency characteristics

Range: 50 kHz to 65 MHz in 6 bands (50-170 kHz, 165-560 kHz, 0.53-1.8 MHz, 1.76-6 MHz, 5.8-19.2 MHz, 19-65 MHz); total scale length approximately 95 in.

Accuracy: ±1%.

General

Power: 115 or 230 volts ±10%, 50 to 400 Hz, 135 watts.

Dimensions: cabinet mount, 20¾" wide, 12½" high, 14¾" deep, (527 x 318 x 370 mm).

Weight: cabinet mount, net, 53 lbs (23,9 kg); shipping, 64 lbs (28,8 kg); rack mount, net, 48 lb (21,6 kg); shipping, 62 lb (27,9 kg).

Tony stated that for most of the research and development work done in H-P labs, signal generators must have an accuracy of 1%. He stated further that 1% accuracy is a pretty general requirement for electronic research equipment and that this is usually the kind of accuracy aimed for when new equipment is being designed. (Some equipment of course, such as that used for calibration, must have an accuracy one or two orders of magnitude higher.) One percent accuracy means that if the generator indicator is set by the user for 100 cycles per second, the generator must produce between 99 and 101 cps. If he sets the indicator or read-out for one megacycle, then the generator must produce one megacycle plus or minus 10,000 cycles per second.

Tony said he found out the hard way that the best way to get this accuracy was to calibrate the read-out of each signal generator individually. (Determine with other instruments what frequency a signal generator was actually producing and then scale or mark its read-out accordingly.) He once tried to devise a method of varying the frequency so accurately that a pre-scaled read-out could be used on every generator of that model, and still have an accuracy of within one percent. It used some intricate non-linear cams and compensating devices.

"The problems began when I discovered that even the most precision ball bearing and shaft assemblies that I could get still had small amounts of play, even if less than 1/10,000 of an inch. I had to be able to predict exactly how the cam and its compensating devices would vary the L and C as the control knob was turned. I had to take into account the play of the bearings in the races and on the shafts. I even had to consider the infinitesimal amount of torsion and flex experienced by the shafts. I nearly went crazy trying to formulate the mathematics for the thing. I finally wrote to one of the best ball bearing companies in the business and asked if they could help me. They replied that they'd had two men working on a similar problem for five years just trying to write a computer program for it. It finally took me two months just to figure out some approximations for it. I ended up with a system of cams, shafts, counter-shafts, and counter-compensating devices so complex that I still shudder when I think of it. The cost of the thing was astronomical. The whole episode was one of the worst engineering experiences I have ever had. I'll never try to 'brute force' a project like that again. Before I even started the preliminary design of this read-out, I felt that I wanted the signal generator to be individually calibrated* Many of our other instruments are individually calibrated but with varying degrees of cost."

* The process of individually calibrating a dial requires the printing or scribing of scale divisions on the dial after determining the operating characteristics of the instrument. The person calibrating has a master instrument or standard whose characteristics have been determined to a high degree of accuracy. At specific increments, he matches the output of the new instrument with that of the standard, and then marks the reading of the standard on the dial of the new instrument. In some cases, the process can be automated reducing the time necessary to perform the operation and also reducing labor costs.

Tony stated that labor coefficients are high. Ten dollars direct labor cost might add $50 or more to the selling price of the finished product, (thus a coefficient of 5+.) Since labor costs a company considerably more than just actual wages, labor coefficients may be twice material coefficients. Accordingly it is important that the amount of individual handling necessary to produce any device be kept as low as possible. Now, if the finished signal generator is to sell for $1500, the read-out part cannot cost more than $120. If there is a cost and labor coefficient of 3*, then parts, labor and calibration must cost under $40 or approximately $13.50 per read-out.

Types of Read-outs

Of the types of read-outs shown in Appendix "A", the 'fixed scale (linear) moving indicator', the 'lighted digit' and the 'Veeder-root' (mechanically turned digit wheels similar to a car odometer) are examples of linear read-outs. The log scales used on some of the dials and meter faces and on the 'rotating drum' are examples of non-linear read-outs. The capacitive and inductive elements which vary the frequency of the output waveform (see Appendix "B") are linear elements. One revolution of the cam varies the L-C combination by a specific amount Z. Three revolutions of the cam (assuming now that the cam is linear) and L-C combination varies by $3(Z_x)$. Frequency however, varies by the relationship:

$$F_o = \frac{1}{2\pi \sqrt{LC}}$$

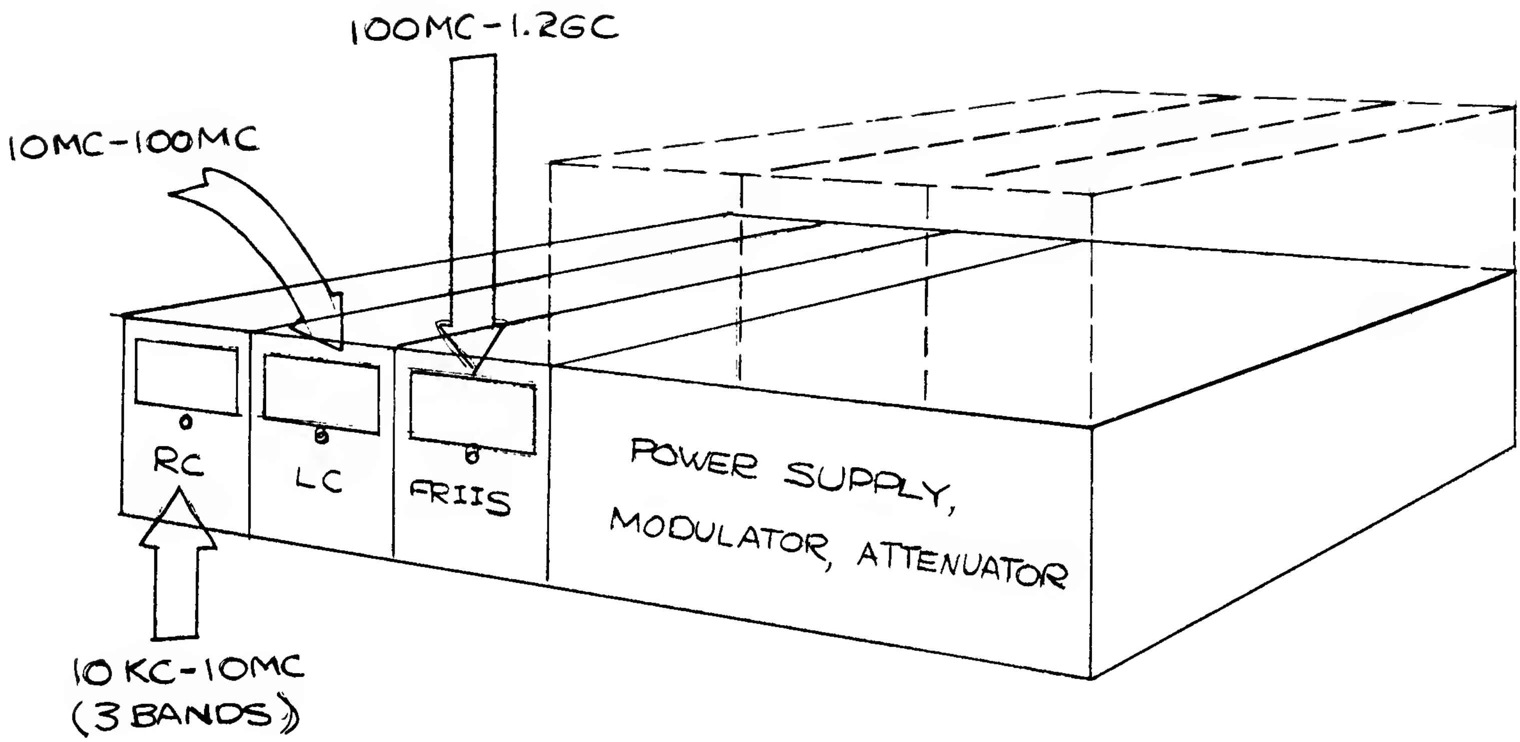
so that as the cam turns one revolution, frequency varies hyperbolically, The generator itself only has the capability of 1% accuracy. A read-out might say 'accuracy of .001%', but the actual output would only be within one percent. These were facts that Tony decided he should consider in designing the read-out. Tony says that he also felt that the future size of signal generators should be considered. "Eventually we may be able to reduce them to the size of a sugar cube."

* These figures are purposely fictional but should give some feeling for the cost problem.

Tony said there was pressure from management to use a linear readout such as the Veeder-root. "The lab manager once worked for a company which spent two million dollars in R and D for a small non-linear readout. Their project was a complete failure. My major concern is with the people who buy and use this machine. I think it's doing them a real disservice to give them a machine which reads out more accuracy than it actually provides. To me this is more important than the preferences of management. It's a little risky, but sometimes management will forget about you for a while and if the next time they come around to see you, you have some tangible results, why so much the better. And let's face it, if you're going to look for approval from management for every step you take, you might as well forget it. You'll get nowhere. Anyway, this is something else to consider. Management can't be ignored, but on the other hand, I don't want it to influence me into making what I feel might be a bad decision."

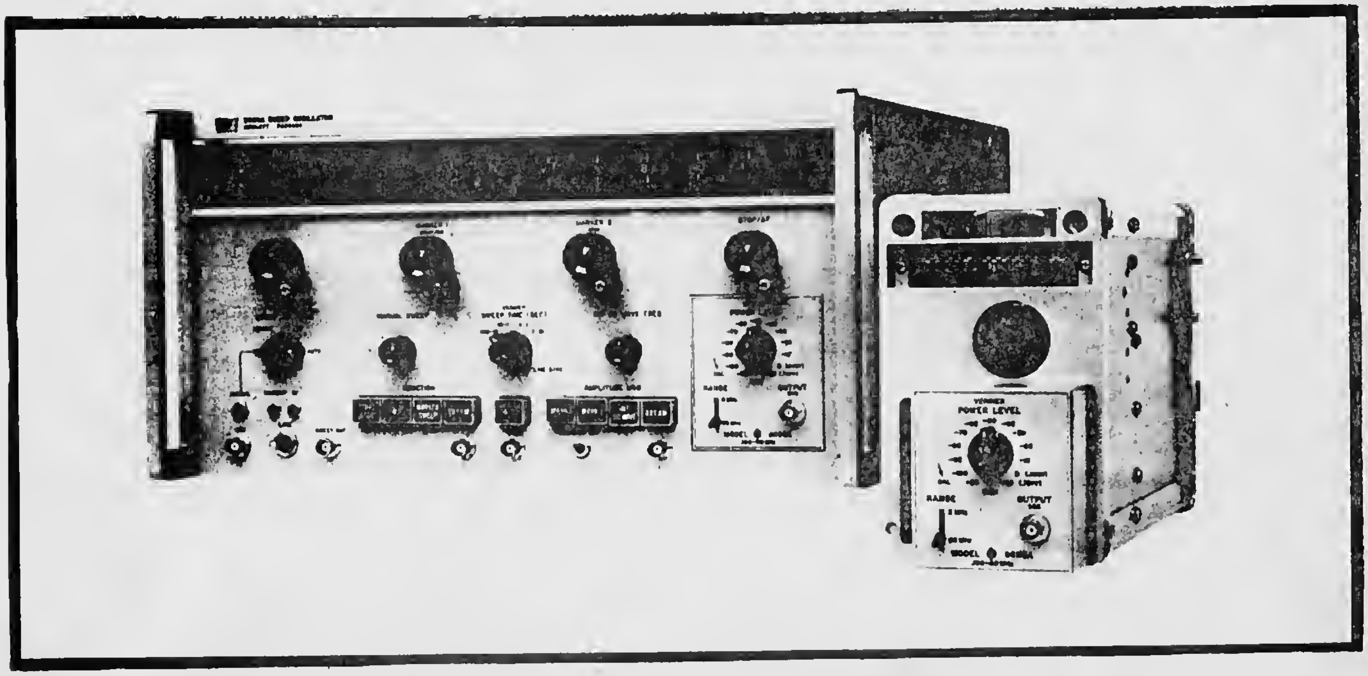
Dimensions

Tony wanted to package the signal generator in four modules which when mounted side by side, could be used in a rack. He assumed the power supply module would be as wide as the sum of the widths of the other three modules, so that the three modules could be mounted atop the power supply. Each of the three frequency modules would need its own read-out on the front. This would allow the different mounting arrangements. A control is also needed on the front to turn the barrel cam (and thus vary the frequency). Jacks or plugs may come out of the back of the module. Each read-out will cover a range of from 10 to 120, for example of from 10 to 120 megacycles.

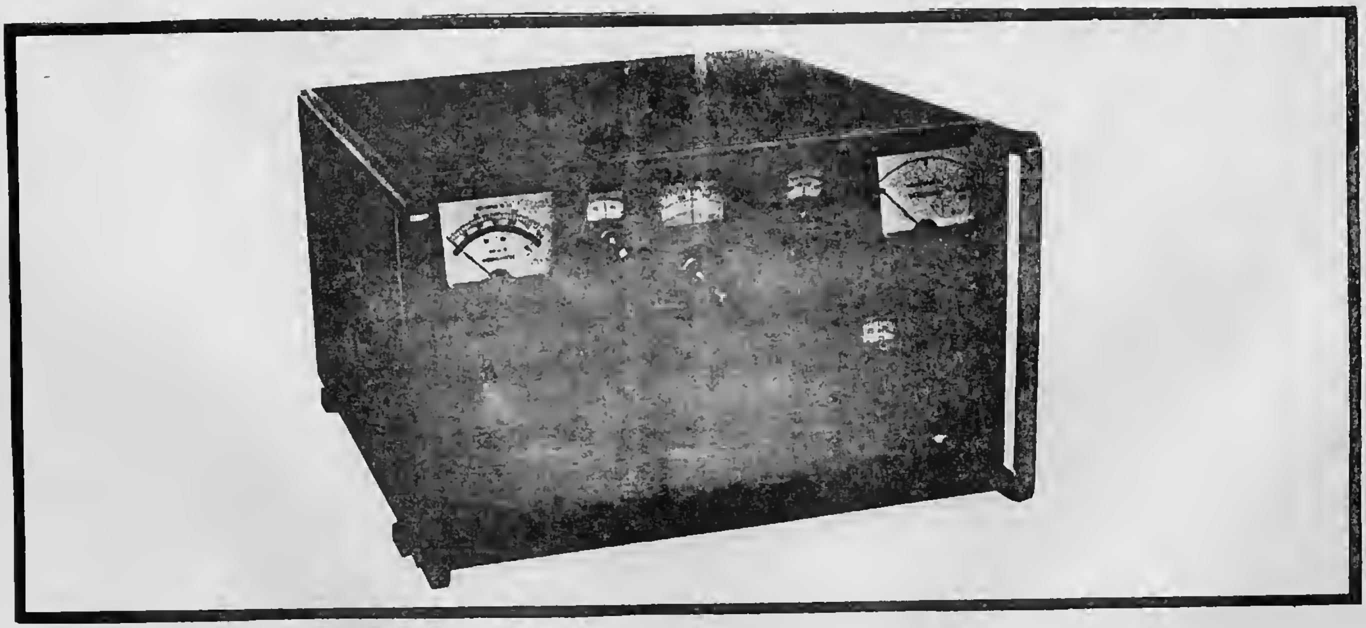


SIGNAL GENERATOR LAYOUT

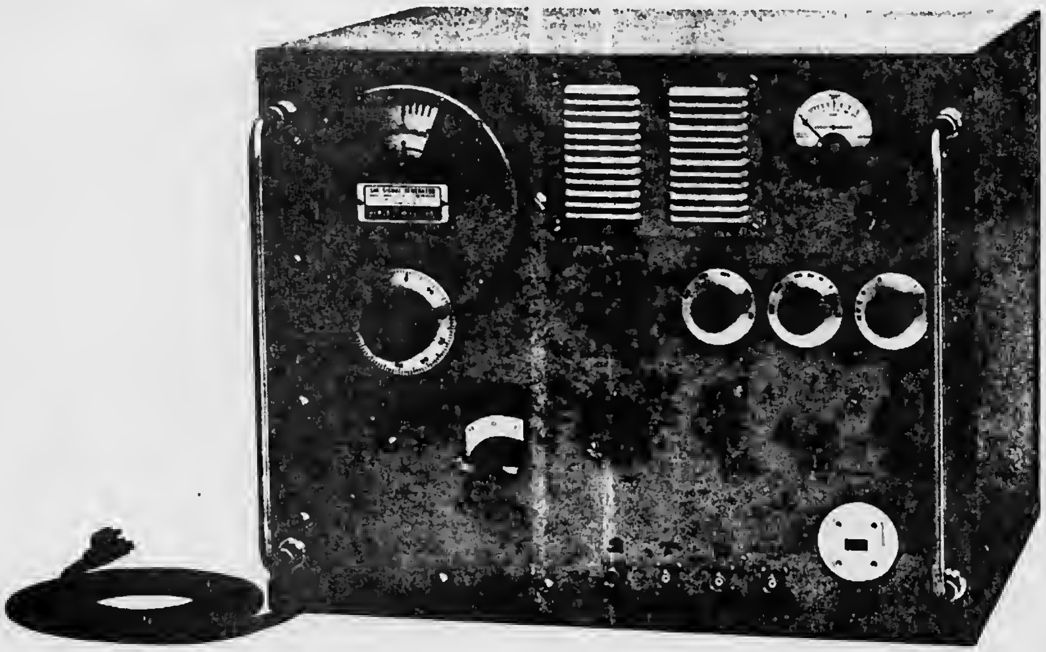
REVOLVING DRUM LIGHTED NUMBER DIGITAL VEEDER-ROOT



FIXED SCALE (LINEAR) MOVING INDICATOR



METER FACE READ-OUT REVOLVING DIAL AND VERNIER

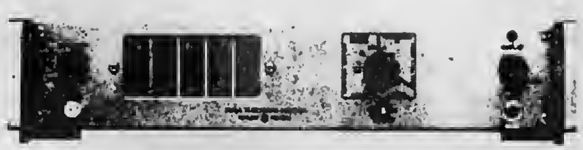


628A

GEAR DRIVEN ROTATING DIAL AND VERNIER

H22-5211B

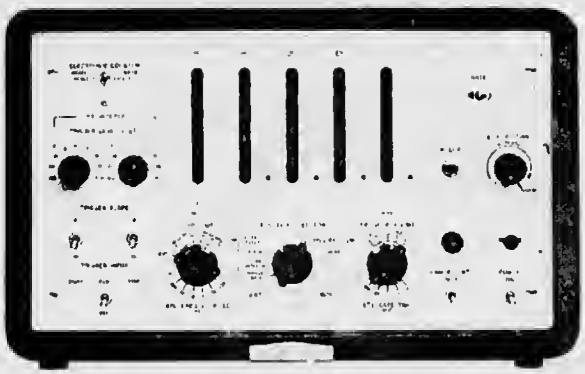
5232A



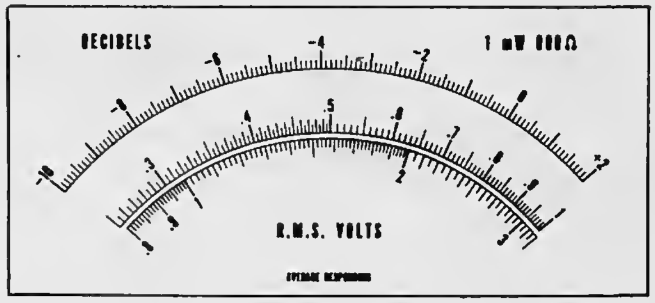
5212A

LIGHTED NUMBER DIGITAL

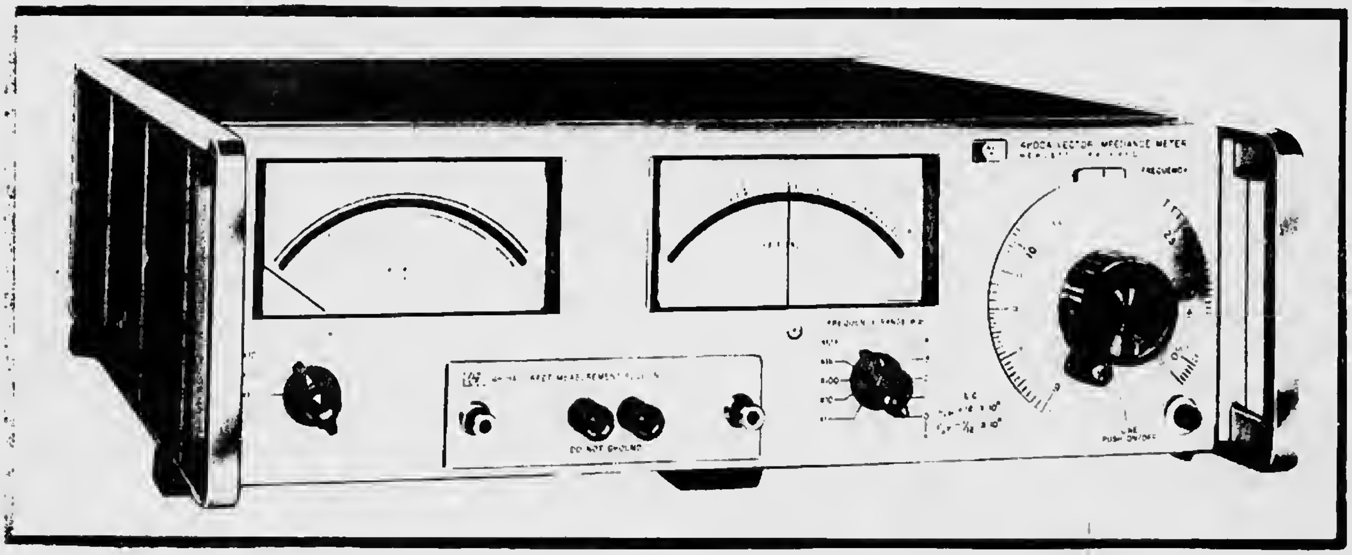
LIGHTED COLUMN DIGITAL



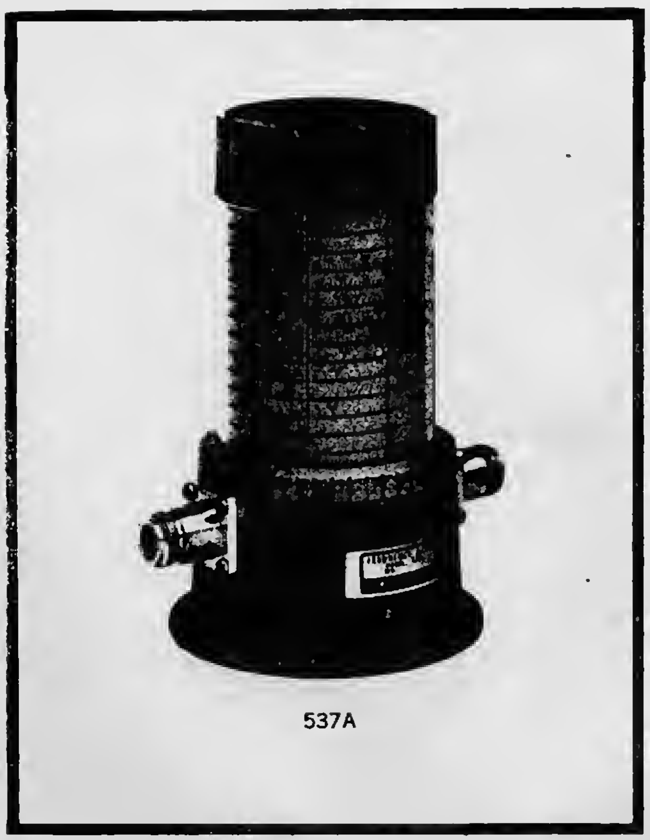
LIGHTED COLUMN DIGITAL



LOGARITHMIC METER SCALE



LOGARITHMIC METER FACE READ-OUT ROTATING DIAL



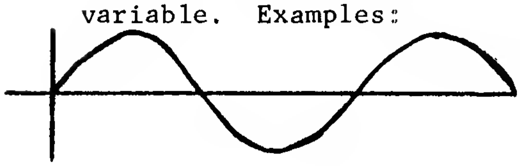
ROTATING DRUM

LINEAR METER FACE READ-OUT

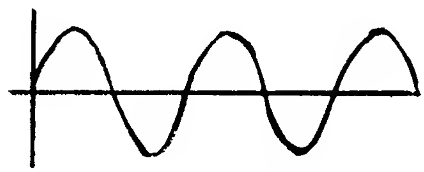
APPENDIX "B"

Electronic lab work often requires an electrical signal, useable as either a voltage or a current. It may be required as DC, direct current, such as that supplied by a battery or as AC, alternating current, which means the polarity of the current is continuously reversed at a certain rate. The rate of this reversal is important. The rate, of course, is dictated by the application for which the signal is used. Normal house current is AC and undergoes 60 polarity reversals per second. It may be said to have a frequency of 60 cycles per second. Since lab work may require reversal rates or frequencies from a fraction of a cycle per second to literally billions of cycles per second, the only practical method of supplying such signals is to have a device which produces a signal of variable frequency, thus the signal generator.

The signal generator produces a wave form whose frequency and amplitude may be varied. Sometimes the shape of the waveform is also variable. Examples:

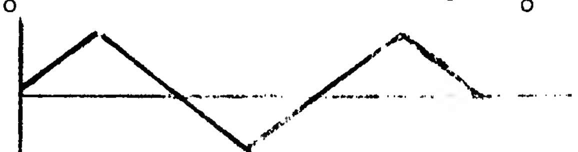


sine wave of freq. F_o



sine wave of freq. $2F_o$

changing amplitude



changing shape

Signal generators have many uses. In electronics research, repair (trouble-shooting), and alignment, the use of a signal or waveform over a range of frequencies is often required. The signal generator can provide a waveform (depending on the model) of from zero to 5 x 10^{10} cycles per second. A researcher may wish to know how a circuit responds to a signal of some frequency. He may examine the circuit response by putting the circuit output on an oscilloscope. The new shape, size and phase shift will tell him what he wants to know.

Repairmen use signal generators to align receivers of almost every description (AM, FM, TV, etc.). Using the signal generator waveform as a standard, circuit adjustments are made until transmitted signals are equal to the standard waveforms.

Because faulty circuit components leave their "fingerprints" on a test waveform, a signal generator is often used in isolating difficulties or pinning down bad components.

Signal generators work on the principle of varying the output of an oscillator with a variable inductor (1) and/or a variable capacitor (C). (See illustration below.) Resonance,(very roughly, when a circuit shows it's smallest possible resistance and thus passes its largest current) occurs when $\omega o L = \frac{1}{\omega o C}$ where ωo equals resonant freq. in radians per second. Thus, $\omega o = \frac{1}{\sqrt{LC}}$ or $fo = \frac{1}{2\pi\sqrt{LC}}$ cycles per second.

There are many types of oscillator circuits but they generally have in common the property that the frequency at which they oscillate is dependent on the frequency at which resonance occurs. Since both L and C may be varied, the resonant frequency F_o (and hence the frequency of the oscillation) may be varied.

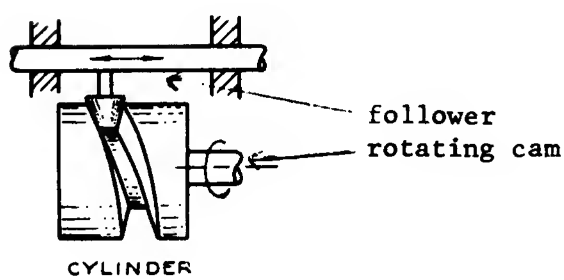
A signal generator also contains circuits for amplifying the oscillator output, removing DC components, smoothing out a waveform and/or changing its shape.

APPENDIX "C"

The actual components which vary the frequency of the output are new and rather unique, and to avoid making things any easier for Hewlett Packard's competition, Tony preferred not to say too much about them.

We may, however, for the purposes of this case, assume that each of the three frequency modules contains a capacitor and an inductor which are varied simultaneously by a barrel cam. A barrel cam is a spirally grooved rod somewhat like a thick drill bit. The cam differs from a bit in that its grooves need not have a regular pitch, and therefore need not vary the L and C in a regular manner. One may easily, in fact, design a barrel cam whose grooves vary hyperbolically, parabolically, exponentially, logarithmically, sinusoidally, etc., etc., or any combination thereof. (See illustration below.)

This cam movement is what is meant by "mechanically variable." A knob and a set of reduction gears turn the barrel cam, and the cam follower, which rides in the twisting grooves, varies the inductance and capacitance.



produces horizontal motion the speed of which depends on the pitch and angular velocity of the cam.

"We are constantly looking for ways to improve our signal generators," said Tony, "They are a five million dollar a year business at H.P. and represent 22% of the company's sales. We can't afford to let our competition get ahead of us. Some of H-P 's high frequency signal generators were originally designed 15 years ago but we hadn't been able to improve these very much until recently. Design had been limited by the size and nature of the components these generators used. By today's standards the old models were big and heavy and had definite stability problems.* We wanted to make them more stable and at the same time smaller and lighter. I sensed from the beginning that shrinking the read-out to fit a smaller overall package would be a problem. In fact I wrote a memo to management stating this back in September of 1965 when I was still investigating components."

Tony, who held a B.S. in Mechanical Engineering from Stanford, headed the research and development group which was to investigate these improvements. Tony initiated the project when he requested managerial permission to look into ways to improve certain components related to varying the output of high frequency signal generators.

His first assignment at H-P in 1960 involved calibration of high frequency signal generators, which weren't meeting their frequency drift specifications. Each generator had different output characteristics and trying to calibrate them on the assembly line proved to be expensive and time consuming. The solution at the time was to make internal adjustments in each unit until the generator met specifications, and the labor costs for this were high. Tony was assigned to look into why the output of this mass produced signal generator should be as unpredictable as it was.

" I really got involved. I worked late nights and weekends for over six weeks. I finally decided that the mechanically tuned oscillator components which varied the frequency of the output were at fault. I tore them down and analyzed them till I probably knew more about mechanically tuned oscillator components than anyone else at H-P I submitted a report stating the problems and how I thought the components might be improved, but the boat didn't exactly get over-turned. That is, nothing much came of my report. Ever since then though, I've been really interested in this component problem. Finally in August of 1965, I asked for time to look into it further."

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*14"x17"x21" and 65 lbs. The present sig. gen. are susceptible to what is known as 'microphonism', the vibration of oscillator tuning elements (the variable capacitor and inductor begin a self sustained vibration) due to slight vibrations in their environment. The small fan motor which cools the sig. gen. might be enough to start this off or even the vibrations from footsteps of people walking by. Microphonism causes freq. modulation or sudden fluctuations in the freq. of the output. Variations in temp. also cause the output to vary. Even the heat from the generator's own tubes could cause this type of instability.

HEWLETT-PACKARD CORPORATION VI (B)

Signal Generator Read-out Design

A Read-out Solution

"I didn't know exactly how small the read-out would have to be," Tony Badger recalled, "only that it was going to have to be smaller than anything we presently made. I started making some sketches of the front of the module, and get the idea of using Neg'ator tape. (Exhibit A).. I had once seen a catalog from the Neg'ator Company showing their tape used as dials."

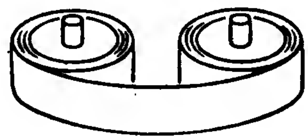
Tony made sketches of a module front 2.825 inches high and 5 inches wide. This space he divided into two areas, one about 1x2 inches near the top center for the tape read-out, and one about 1-1/2 x 2-1/2 inches below the read-out for possible gear arrangements and knob locations. The gears were between the knob and the tuned elements and had a three-to-one ratio. The read-out was driven by a gear and shaft connected to the gear reduction unit.

"We got busy working on some other parts of the design so it was about a month later when I worked on the read-out again, that is, other than just occasionally thinking about it. I decided to list advantages and disadvantages of all the different types of read-out methods I could think of (Exhibit B) but the Neg'ator tape still seemed the best solution. Its stability, strength and simplicity were the main reasons I preferred it. It would seem as if all we had to do now was silk-screen the scale on the tape, drive it with a sprocket like those in the Neg'ator catalog, and we would be finished. Unfortunately, things usually don't work out that easily.

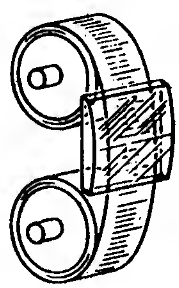
"From an experience in designing a signal generator a few years ago (described in part A) I was quite sure we would have to calibrate each scale individually. That ruled out silk-screening. We individually calibrate some of our scales on other instruments now. It's an expensive operation because of the labor cost. So one of my problems was how to apply a calibrated scale to the tape at a lower cost than our present operation.

using NEG'ATOR BANDS as self-coiling printed metal tapes

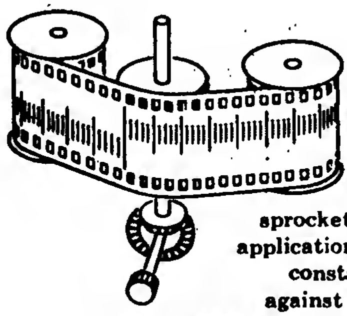
The NEG'ATOR is a flat, thin band of spring steel formed into a prestressed coil. It resists uncoiling uniformly, and provides the same rated force at any extended length.



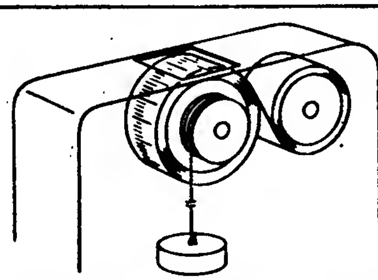
When both ends of the NEG'ATOR are mounted on bushings of equal diameter, the opposing forces are always in balance and the span between the bushings is held taut. Tapes can also be mounted to wind up in housings or cases at each end rather than on bushings.



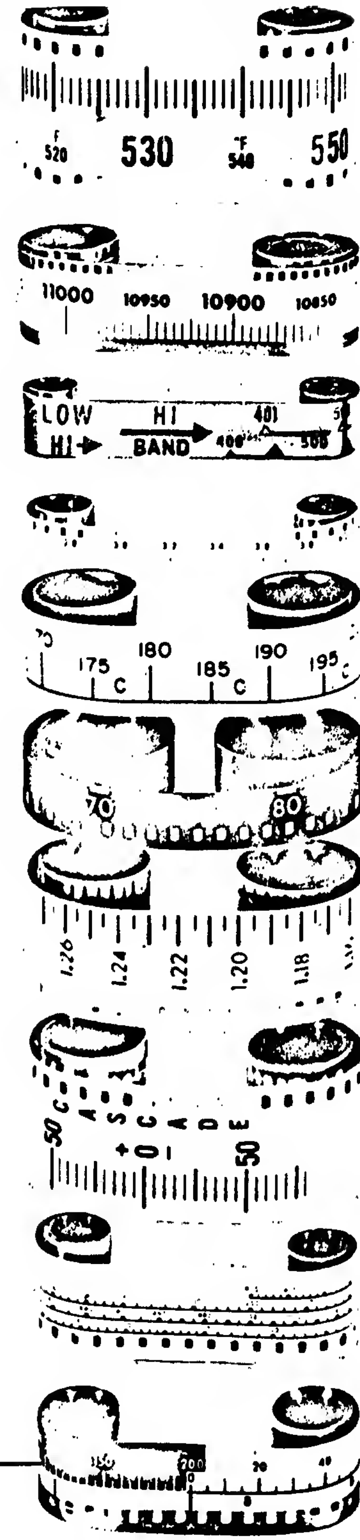
A graduated scale printed on these self-coiling bands can be stored on the drums, and "read out" on the span. Scales in excess of 25 feet in length can be housed in a compact instrument head.



Tapes can be threaded somewhat like movie film for sprocket drive. In such applications, tape applies constant spring load against sprocket teeth, eliminates possibility of backlash.



When one end of a NEG'ATOR tape is curled on a bushing and the free end is reverse wound around a second, larger bushing, the material tends to recurl to its preset curvature around the smaller bushing. This produces a constant force (torque) which can be used as a source of power or to counterbalance a weight such as the float on this liquid-level indicator.



NEG'ATOR Printed Tapes should be considered where endless belt, drum scales, straight scales, or disc scales are now used. But their use need not be limited to expanded-scale applications. Instructional data or indicator signals can be printed in a variety of colors, on narrow bands or on wide scrolls. Typical applications are shown on the following page.

Tapes shown above are under tension to expose a broader expanse of scale. The illustration in the adjacent column more accurately depicts the condition of the outermost turn in relation to the relaxed coil.

2-1-66
NBB

Types of readouts -

negator -
1.) good resolution in small space
2.) can individually calibrate

drum -
1.) can individually calibrate
2.) takes up more room for same readability

counter (Veedervoot) -
1.) can not individually calibrate
2.) small space & good resolution
hence requires cams that are calibrated

linear scale -
1.) can individually calibrate
2.) takes up room
3.) limited resolution

2-1-66 ASA

Ray Grant — Eastman Kodak
Ph. 66055 Jack Welsh — recommended

film -

advantages -

1.) Can process in our plant

cost? - film tape might be cheaper than metal

disadvantage -

1.) not as durable as metal - may not be possible to drive @ road out pt. & not wear out sprocket holes

2.) requires more elaborate drive mechanism

a) ~~tensioning~~ cable

b) tensioner

c) better frictionless brgs - probably ball brgs. - this is necessary to reduce load on driving sprocket holes also to prevent backlash due to tape stretch

d.) ~~also~~ pulleys instead of posts

4.) Doesn't resist environmental conditions as well as metal -

a) moisture

b) heat

c.) stretching

3) Not dimensionly stable - more care must be exercised when puting on calibration lines.

2-1-66-AB

2. metal tape –

This disadvantage may be eliminated (if we could process tape photographically – only question – wear resistance.

advantages –

1.) dimensionally stable.
2.) durable – can drive at readout pt. with no problems
3.) makes drive system very simple i.e. no idlers or tensioning devices or elaborate brgs.
4.) Good environmentally – except rust maybe

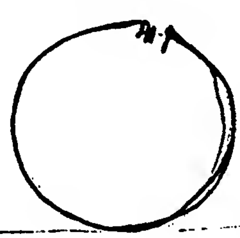
disadvantages –

1.) Cost ?
2.) environmental – rust?
3.) Can't process in our own plant.

If we could do this photographically we might be able to process here. —

a.) buy tape painted white & curled – spray with photo emulsion

wrap tape around drum & do like 536 dial.



"I assumed a linear scale about 13 inches long and that the smallest division would be 1/16 of an inch. I estimated that the 1/16 inch division could be divided into five parts by the eye. The accuracy we expected from the generator was $\pm$ 1% of the frequency at which it is operating. That means if the generator is set at 100 MC it could be putting out 99 to 101 MC. If the generator is set at 10 MC the output could be 9.9 to 10.1 MC. I wanted a scale that would allow the operator to set the dial just a little more accurately than the generator's output because I didn't want the accuracy to be limited by the read-out. After going through some calculations, (sample in Appendix 1) I decided we would be fooling the customer if we used a linear scale. If we made the linear scale large enough to obtain $\pm$.1% accuracy at the lower range, we would have 10 times the accuracy ($\pm$ 0.1%) at the higher range. The customer might think he could set the generator output to 98.6 MC because the linear dial could be set to this accuracy. If he put the generator on a scope, he would see this is not true. We have tested other instruments that have this fault. I'm not saying that the instruments were not as accurate as the manufacturers claimed. They were. They just gave you the feeling, for part of the range, of having a greater accuracy than they did, I feel the scale should reflect as closely as possible the true output of the instrument.

" I saw that the accuracy was 10 times better on one end of the scale than on the other. A log scale would give a truer picture of what was happening. I picked up my slide rule and tried setting the frequency on it. If I had a log scale about two slide rules long, the dial would be just right. I had our computer programmer write a program for the layout of a log scale to be put on 16 mm tape and driven by a standard film sprocket. (15 teeth, 0.150 pitch). The computor program determined the coordinates for each division and an overall scale length of 25.25 inches for a range of 8.5 MC to 115 MC.

"The next question was how to apply this master scale layout to the tape and calibrate it at the same time. Some tests and models would have to be made so I brought Pete Rich into the design group to work on the read-out problems."

Peter Rich joined Tony's design group as a technician in May 1966. His experience as a technician started when he was trained by the Army in their Microwave Radio School. He completed the rest of his enlistment as a repair Sergeant for microwave equipment. Upon his release from the Army, Pete went to college but studied non-technical subjects. Following college, he joined Hewlett-Packard and in the 4-1/2 years before joining Tony's group, worked at a variety of positions such as technical writer, tester, and supervisor in charge of a production line. Pete was working as a technical writer when he met Tony and expressed an interest in working with a design group. He was working as a technician in the Wave Guide Assembly Area when Tony requested he join the design group.

"To get Pete started on the project," Tony commented, "I showed him some of the ideas I'd had up to that time. We were both photographers so we worked out a system whereby a 16 mm stainless steel Neg'ator tape, with sprocket drive holes along one side, (Exhibit C) would be coated with white paint and then a photographic emulsion.

"For each gradation, a light source would be flashed through a film negative against the photosensitized tape. The tape could then be developed just like a photographic print. But we needed a way to trigger the light source at exactly the right place on the tape. Since the tapes tended to coil up on themselves during spraying and handling, we decided to mount them on drums. Peter suggested that the tape might be magnetized at the increment points with something like a tape recorder head. Each time the standard and the new unit matched frequencies a point on the tape would be magnetized by the head (Exhibit D). The tape would then be passed in front of a second head. When the second head detected the magnetized points, it would trigger the light. In this way each read-out would be calibrated to the unit with which it was to be assembled. Pete found out from our tape recorder design group that a 'Hall-effect' head would be needed for this operation."

The 'Hall-effect' head, made by Applied Magnetics Corp., is a special kind of magnetic recording head. It is basically an electromagnet with an exposed gap or break in its core. This gap is generally only a few thousandths of an inch wide. When current is passed through the electromagnet, a magnetic field is created in the gap. Objects passing close to this gap become magnetized. When the electromagnet is off and a magnetized object is passed in front of the gap, a voltage is induced in the head. This voltage, though on the order of microvolts, can be amplified to trigger a light source. The 'Hall-effect' head differs from conventional recording heads, in that the induced voltage does not depend on the speed at which the tape passes the gap. In fact the head works best when the tape is not moving at all. This velocity independence is important when trying to find the exact peak of a pulse.

Pete said, "I got the idea of using a tape recorder head because I had worked with them at home. I don't know if Tony was completely sold on the idea, but he let me go ahead and order one anyway. I built a breadboard fixture (Exhibit C-1) to check the head's characteristics. The questions we had to answer were:

1. Would the head magnetize a small enough point on the tape? If the head magnetized too wide an area, accurate triggering of the light source might be difficult and the increments might run together or be mispositioned.

2. After detecting the magnetized point with the head, should we trigger the light on the maximum voltage induced in the head or just before or just after the voltage reached its maximum? Either side of the maximum would be easier to find but it would be less accurate.

5/30/66

Scroll-like "type" dial in the form of a steel ribbon, coiling upon itself is adopted in the interest of conserving space for the unit's readout - thus:

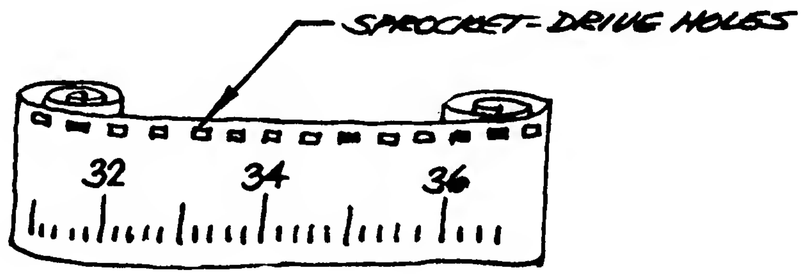
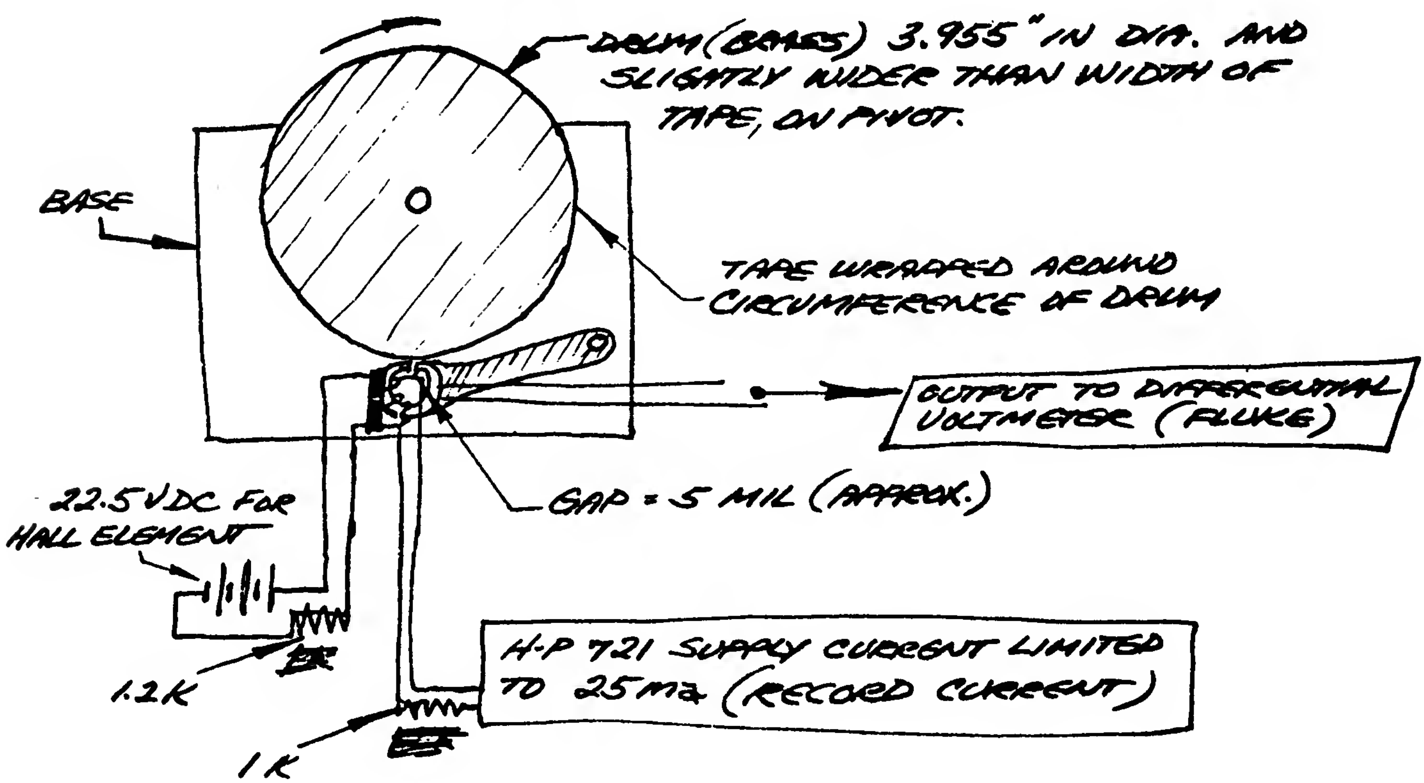


EXHIBIT "C-1" ECL 78-B Page 8

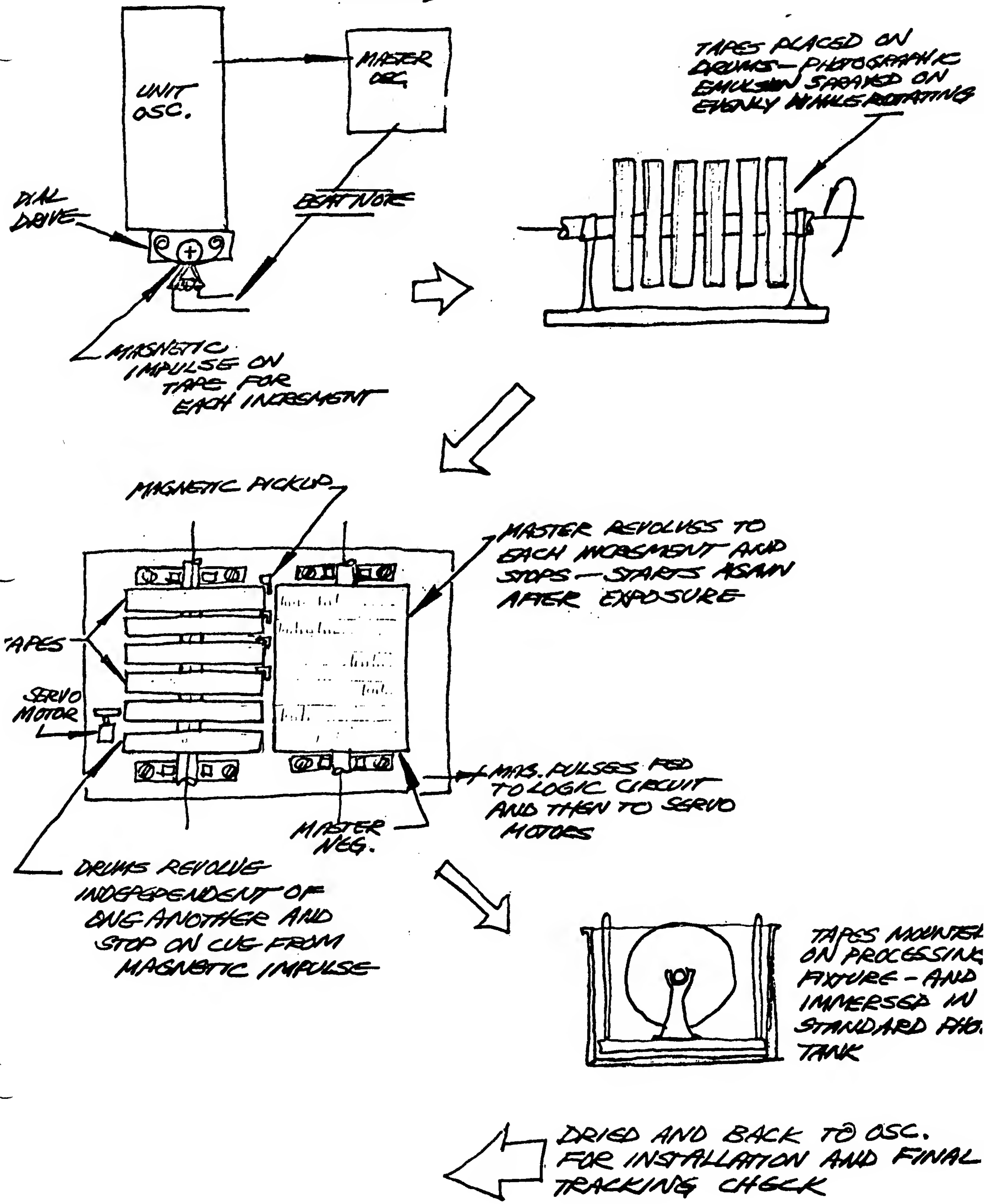
6/3/66

A breadboard fixture was made to investigate characteristics of head:



INDIVIDUAL CALIBRATION METHOD (BASIC)

5/30/66



"I assumed I could get the magnetic head to work properly and started on another problem. Processing the coiled tape was going to be difficult because of a handling problem. The tapes wanted to coil up on themselves and this damaged the painted surface and emulsion. When I tried to hold the tape flat it cupped laterally. I solved this by mounting the tape around the circumference of a drum and secured the ends by rolling the tape around two 16 mm film sprockets. To lock the sprockets I tightened the allen screws which held the sprockets on their shafts. The tape then stayed on this drum for the entire developing and drying process.

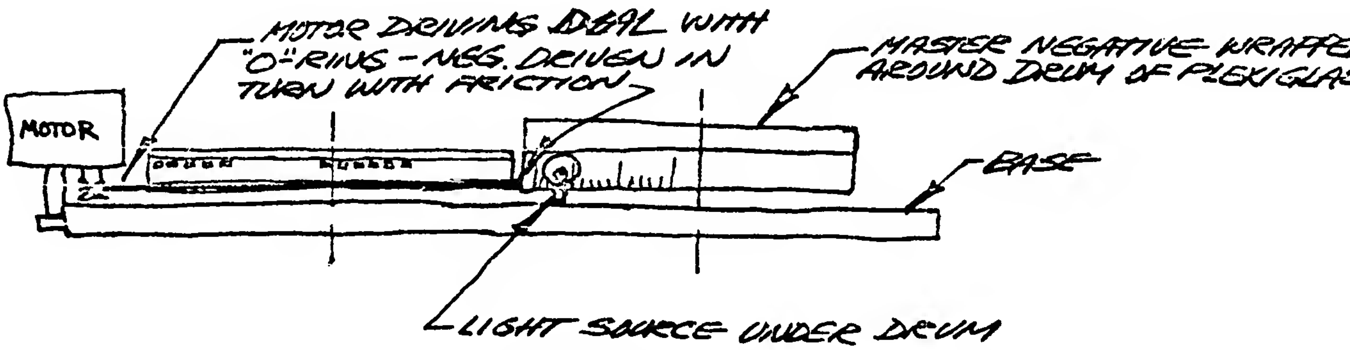
"Next I built a prototype printer (Exhibit E) to test the idea of transferring a scale to the steel tape. I merely passed a light through a transparent scale onto the emulsion on the metal tape. The first tape we processed was 0.003 inch thick stainless steel with sprocket drive holes along its top. (Exhibit E). After a little adjusting of the light intensity and the drive speed, I got a tape with good results. The gradations and numbers were a little hazy here and there due to overexposure, but it proved the feasibility of the idea. Tony sent the sample tape to environmental testing and had it run for 10 thousand cycles under high humidity conditions. A cycle consists of rolling the tape all the way up on one spool and back again. After the test, the tape showed a slight discoloration and a peeling of the emulsion. There were also a few breaks in the tape above the sprocket holes. I think this was due to bending too thick a tape over too small a radius. The next tape processed was a 0.002 inch tape which did not break during the same type of environmental test. There were indications of small cracks in the base-coat paint on this tape, but the tape was O.K.

"Our 'Hall-effect' head arrived. When we made the resolution plot for the response characteristics (voltage induced in the head versus the width of the area magnetized, Exhibit F) we found that we could not obtain the information we had hoped for. We couldn't trigger the light source on the maximum induced voltage because the maximum varied too much from pulse to pulse. We couldn't trigger on either side of the pulse maximum because the pulse was much wider than we expected and we could never be sure what side of the pulse we were on. If we triggered on the wrong side of the pulse, the increment mark would be too far off for the accuracy we wanted. It would take a head with a one mil (.001 inches) gap to get the resolution we needed. This was not a standard head. The company could have made a special head for us, but the cost was too high. Also with such a narrow gap, the point which the head magnetized would probably have been too weak to detect. We were already dealing in millionths of a volt. I sensed that Tony was becoming less enthusiastic about the Neg'ator tape. I could see a number of problems and envisioned some wild fixtures for handling the tapes."

At this point in the development of the read-out, Tony decided to leave the Neg'ator tape and pursue another idea. Tony commented, "It's not that the Neg'ator tape wouldn't work. We could have solved the problems we ran into. We rejected the idea because the labor costs were becoming too high. The tapes were difficult to spray with paint and emulsion. The emulsion bruised and discolored if hit, so each tape had to be carefully handled. We wanted to find a better method with lower labor costs."

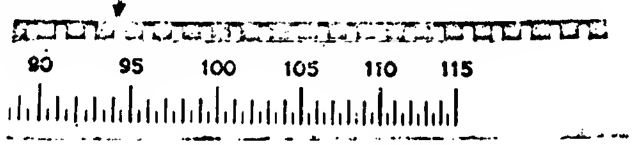
Prototype Printer and Sample Tape

→ A prototype printer encompassing the basic negative to dial relationship was built to gain insight into the basic problems arising in a more sophisticated system:



Speed of driving motor and intensity of light source was variable.

BREAK HERE DUE TO TOO THICK A TAPE OVER TOO SMALL A RADIUS (ENVIRONMENTAL CYCLING)

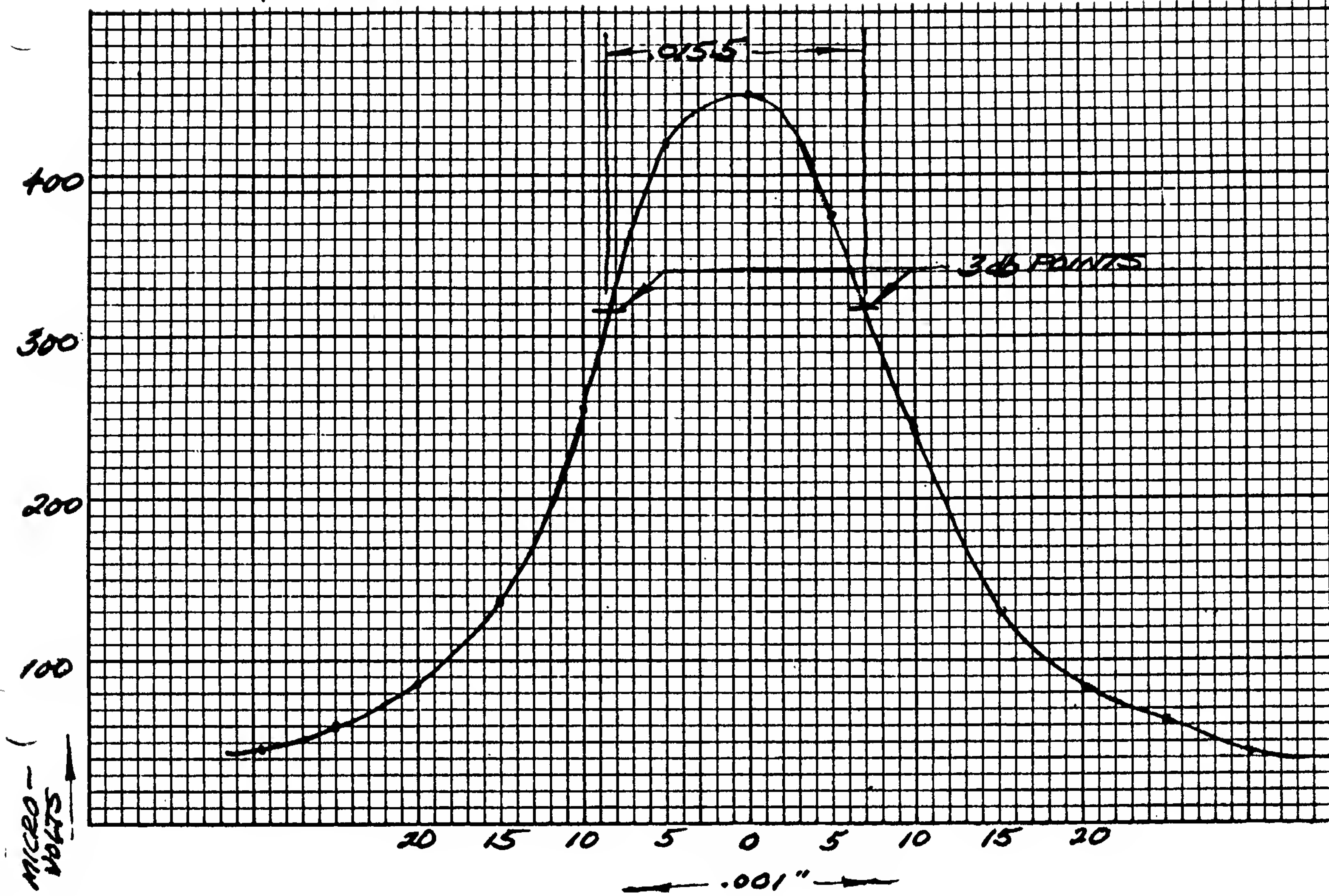


SAMPLE OF FIRST TAPE PROCESSED (.003 thick)

Definition is hazy due to improper regulation of speed vs. light intensity. (Overexposed)

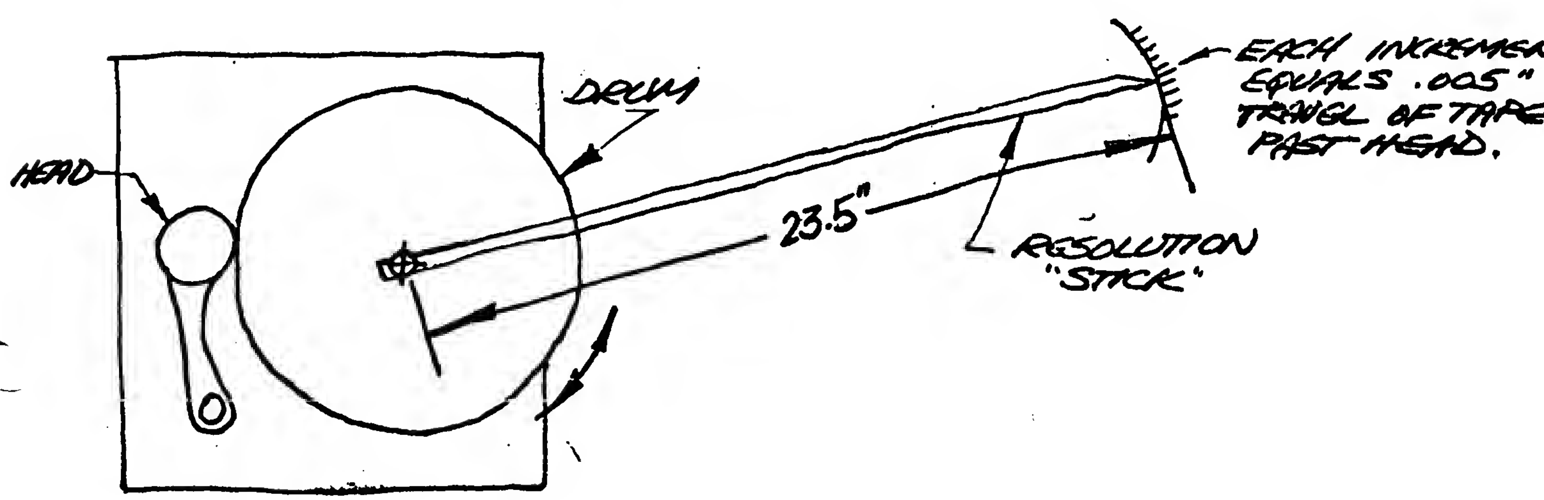
→ Also, discoloration and peeling due to 10K cycles in environmental.

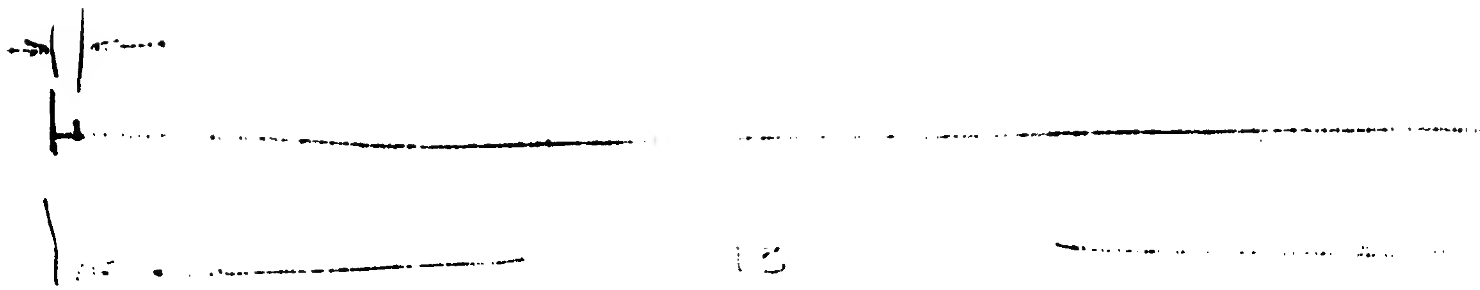
6/16/66



TYPICAL RESOLUTION PLOT OF RESPONSE CHARACTERISTICS –

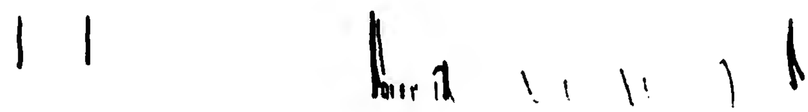
This curve was taken with setup as shown:



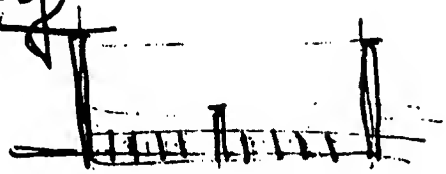


assume max scale length 13"

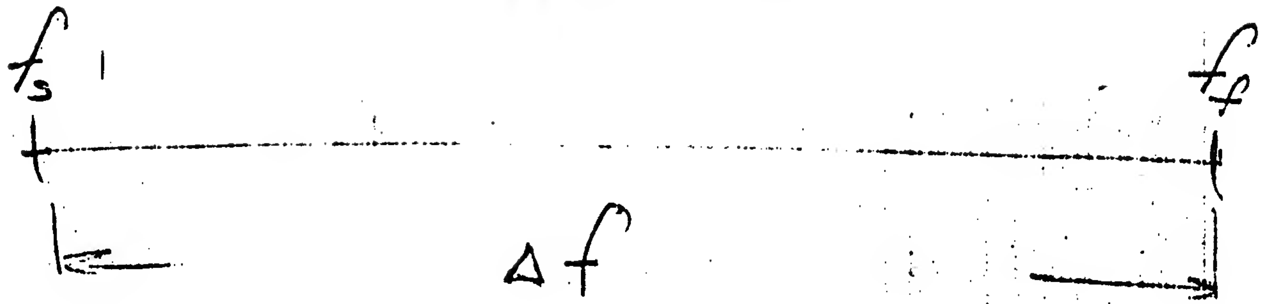
smallest div $= \frac{1}{16}$"



<u>readability</u>



assume that we can read pointer position to within ±.015 of its true position or to within ±1 part in 5 if the $\frac{1}{16}$" interval is mentally divided into 5 equal parts.



the total no of scale div. $= 16 \times 13 = 208$

$\therefore$ each div $= \dfrac{\Delta f}{208}$ increment in freq

we have said that we can read to within ± 1 part in 5 of the smallest div.

$\therefore$ we can read the freq to $\pm \dfrac{1}{5} \dfrac{\Delta f}{208}$

the % error in freq @ each end of the band is

$$E = \pm \frac{1}{5} \frac{\Delta f}{208} \times \frac{1}{f} \times 100 \cong \frac{1}{10} \frac{\Delta f}{f}$$

Range 10–30mc

$\Delta f = 20\,mc$

$\mathcal{E}@_{10mc} = \frac{1}{10}\ \frac{20}{10} = .2\%$

$\mathcal{E}@_{30mc} = \quad .07\%$

Range 30–100mc

$\Delta f = 70\,mc$

$\mathcal{E}@_{30} = \frac{1}{10} \cdot \frac{70}{30} \approx .2\%$

$\mathcal{E}@_{100} = \quad = .07\%$

10:1 Tuning range

Range 1–10mc

$\Delta f = 10\,mc$

$\mathcal{E}@_{1mc} = \frac{1}{10} \cdot \frac{10}{1} = 1\%$

$\mathcal{E}@_{10mc} = \frac{1}{10} \cdot \frac{10}{10} = .1\%$

Range 10–100 mc

$\Delta f = 90\,mc$

$\mathcal{E}@_{10} = \frac{1}{10}\ \frac{90}{10} = 1\%$

$\mathcal{E}@_{100} = .1\%$

HEWLETT-PACKARD VI (C)

Next Approach to Read-out Solution

"Ruling out steel Neg'ator tape," Pete recalled, "left transparent plastic film as the next best idea. One of the reasons Tony had decided against the film originally was that it stretched under humidity and temperature changes. We knew this from our experience with photography."

Such an effect can be seen, for example, by placing a cold photographic slide in a projector. If the slide is focused immediately, the picture will slowly go out of focus as the slide warms and expands.

"What we needed was a plastic film that was dimensionally stable," he continued. "In order to maintain 1% accuracy*, the overall length of the read-out tape could not change by more than .008 of an inch. Commercially available photographic film is made of acetate. I determined from a handbook that acetate didn't have this kind of stability. I knew that high fidelity magnetic tape for tape recorders was very stable. This has a Mylar base. The question was, could I get a Mylar base photographic film. By contacting some of the photographic companies in the area, I found that such a film was being used by NASA for space research. It was being specially made for them by Kodak. I also found that the Japanese were selling a new Mylar base 8 mm film. I mentioned this to Tony. He thought it was worth a test, so I built a fixture to test a sample in our environment lab. The test results were much better than we expected. After running the film for 10,000 cycles on our test fixture, (Exhibit A) there was no measurable elongation. Tony decided we should run the test again and make it more severe. We ran the film for another 10,000 cycles but this time it had to bend more sharply around the drive sprocket. After this test, we noticed a slight fracture at the corner of the film sprocket holes. The film showed no other signs of wear or distortion. Later I noticed the same corner fracture or 'pucker' on a piece of film which had not been tested. It's my guess that the 'pucker' was due to a distortion in the die when the perforations in the film were being punched.

"Now I had to find a way of storing the film in a small package.

---

* The dial length was 24". A total elongation of more than .08 inches would cause an inaccuracy of greater than 1% at the end of the scale at which the increments were closest together. (Remember a logarithmic scale is being used.) Since Tony desired the read-out to be an order of magnitude more accurate than the signal generator, total elongation could not exceed .008 inches.

"The film would have to be coiled on a spool on each side of the read-out. This presented a tensioning problem If we geared the two spools directly together, we got a 'bag' in the film The full spool had a larger diameter than the empty one It unloaded more film per revolution than the empty one took up If we eliminated the slack at this point, the film became too tight when the take up spool became bigger than the unloading one I built a fixture (Exhibit B) to get an idea of the amount of bag we were dealing with

"Tony had the idea of rolling up the film with the Neg'ator tape. I built a fixture to test this idea (Exhibit C) This rolled the film up O.K. , but the tape didn't keep the film tight enough to be read accurately through the bezel The tape also caused the film to wear rapidly.

"My environment test fixture had a tensioning device I thought, 'Why not simplify the spring-pulley technique that I used there?' I knew I could make it into a simple inexpensive package with more effective loading. I made up a fixture to test this idea.(Exhibit D). This also worked well but required too much area. I'd made so many drawings of ideas, in the area Tony wanted to shoot for, that I finally made up a template for this area (Exhibit F). One try of this template over the device ruled it out.

"Tony then came up with the idea of spring loading the gear that would drive the two wind-up spools. I built this fixture (Exhibit E) and found that this worked to solve the varying diameter problem but then other difficulties appeared. As the knob was turned, a fairly 'tight' feeling occured as the film approached either extreme. The short spring I was using was being wound too tightly at these end points. I could have solved this with a longer spring but I wanted to keep the driving mechanism the same height as the spools. In addition, the display area kept getting narrower as one spool emptied The tape made too sharp an angle with the drive sprocket

"In an effort to solve the high spring tension and to flatten the display area, I made up three more test fixtures. In each of these fixtures I was able to improve handling of the film.

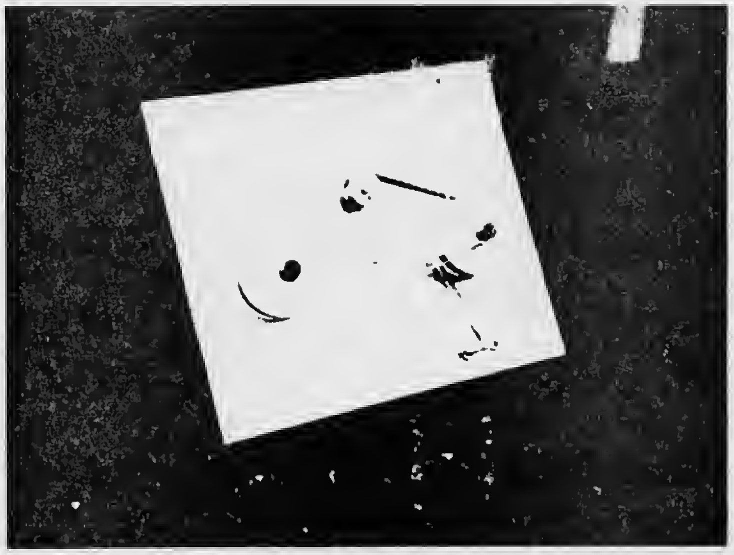
"I put a tension spring in each take-up spool instead of in the driving sprocket (Exhibit H,I,J.). This worked like the spring inside a window shade. One end of the spring was fastened to the spool and the other end was fastened to a gear beneath the spool. When the gear and the spool moved at different rates, the spring wound up and caused a backward tension on the film. An idler gear transmitted the load of each spring to the opposite spool, thus maintaining the constant tension. This took care of the tight feeling at the extremes It also cured the tapering of the display area, since I was now able to increase the diameter of the drive sprocket Now that I had a system that worked, I got the template out and tried to reduce the read-out's size. Once I

got the read-out down to a small area (Exhibit J) two more problems arose. Not only did the sprocket teeth tend to slip out of the perforations in the film, but the film was too hard to read. A background of some sort was needed to set off the numbers of the tape. The solution to the slipping came easily. I used a teflon shoe to hold the film against the sprocket. This shoe also became the bezel which outlined the viewing area. After a little thought and a couple of tries, I undercut the sprocket and sandwiched a background between the film and the sprocket.(Exhibit L). With just a little polishing up of the parts, this turned out to be the final solution to the read-out.(Exhibit K). Even the template for the desired area for the read-out.fit over the entire assembly."

Tony said he was very pleased with this solution because it satisfied all his criteria very neatly. The read-out fit within the desired area and gave the accuracy that was required. It cost less than 50¢ apiece to make and the individual handling was reduced to the processing of the film. Film processing costs only a few cents per unit since fifty or more scales can be processed on one spool of film and the entire operation lends itself to automation. Each section of film can be coded to the signal generator for which it was calibrated and the read-out assembled after the film has been developed. The calibration process itself will be done automatically with a servomechanism.

EXHIBIT "A"

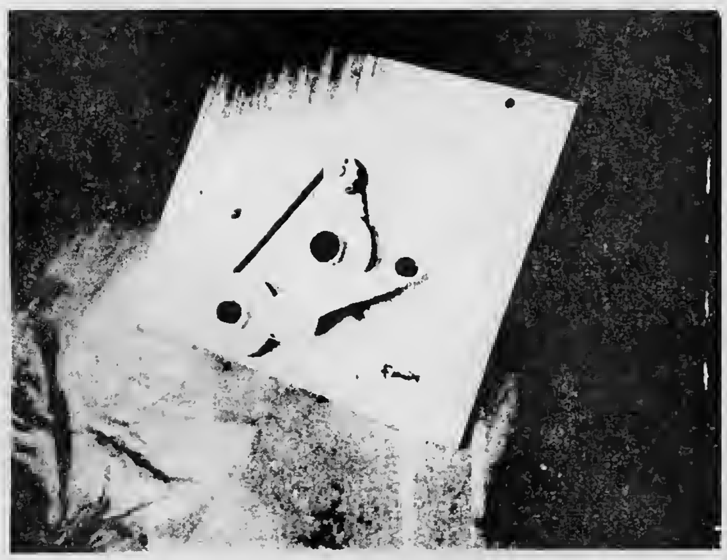
10/17/66

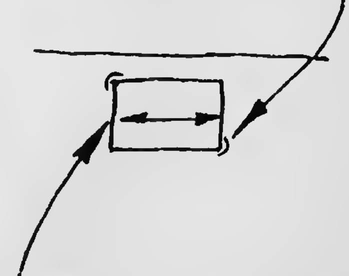


10K cycles in this configuration showed no apparent elongation (microscopic)

10K more with twice as many teeth engaged (4) showed no increased wear due to extra cycles or to increasing severity of radius.

There was a slight indication of corner fracture probably due to the sloppy (compared to regular 8mm) engagement of sprocket tooth in the film.



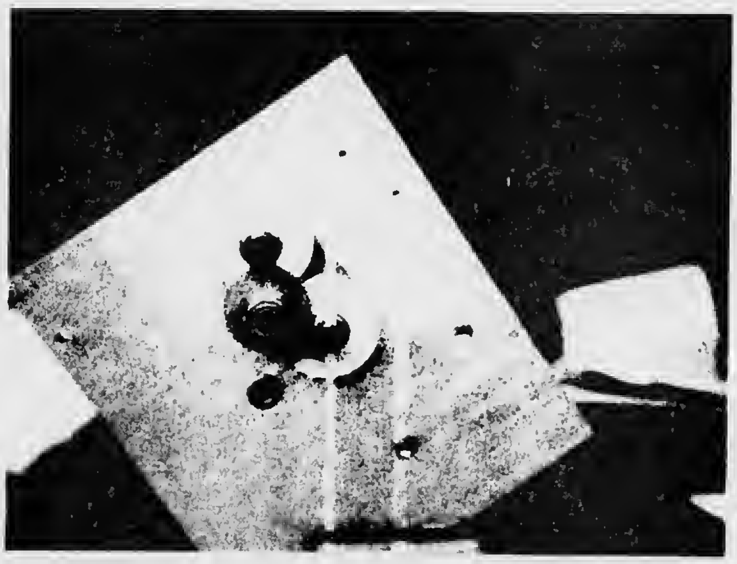


The edges however were unaffected

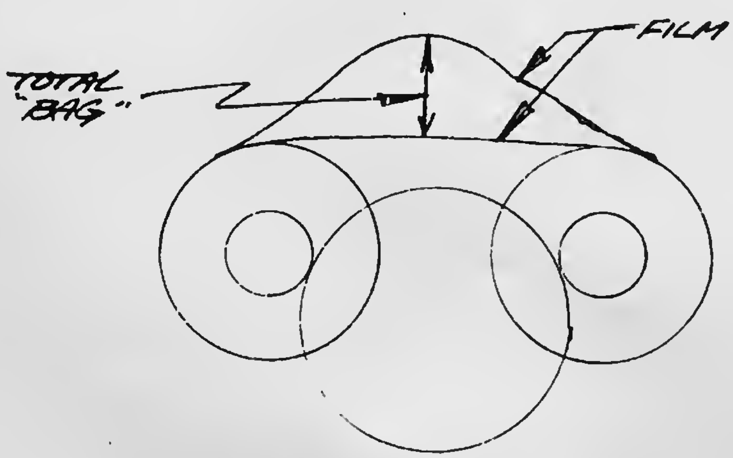
EXHIBIT "B"

11/14/66

Evolution of the investigation of film storage and supply in the small package:



This set-up showed a "bagging" or slack in the total length of the film when spool diameters were geared together:



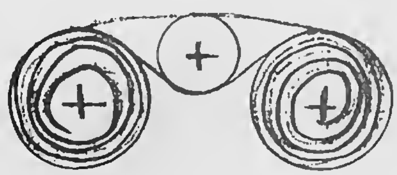
A configuration that provides for a constant tension on the film and allowing for varying spool diameters is desired –

Investigations were tried with double 8MM film.

11/14/66

EXHIBIT "J"

Here is film with steel "negator" tape wound up with the film, and exerting tension on the back of the film.



This set-up works — but does not keep film tight enough to read effectively through the bezel. Also, the wear promoted by the film in contact with the steel is excessive.

→ The objective is a simple, inexpensive package with more effective "loading" than the string and pulley technique. (As on page 13)

EXHIBIT "D"

11/14/66

Another method of gearing with allowance for varying spool diameters:

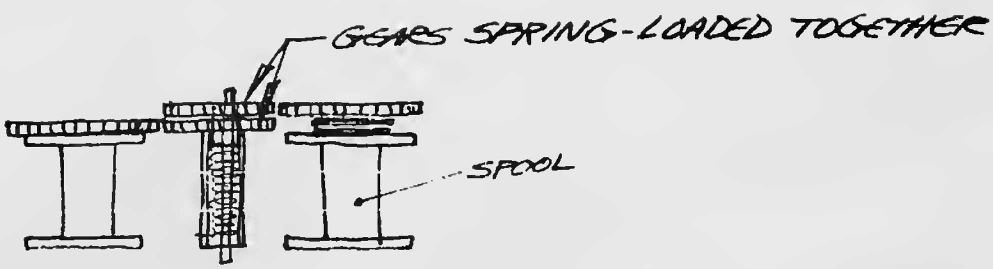
This shows the "baggiest" point in the exchange of film – the tightest point being at either end of the total travel as pictured below:

Slightly awkward and could be expensive –
→ Biggest disadvantage is total "swing" of gear train making larger than desired package.

11/14/66

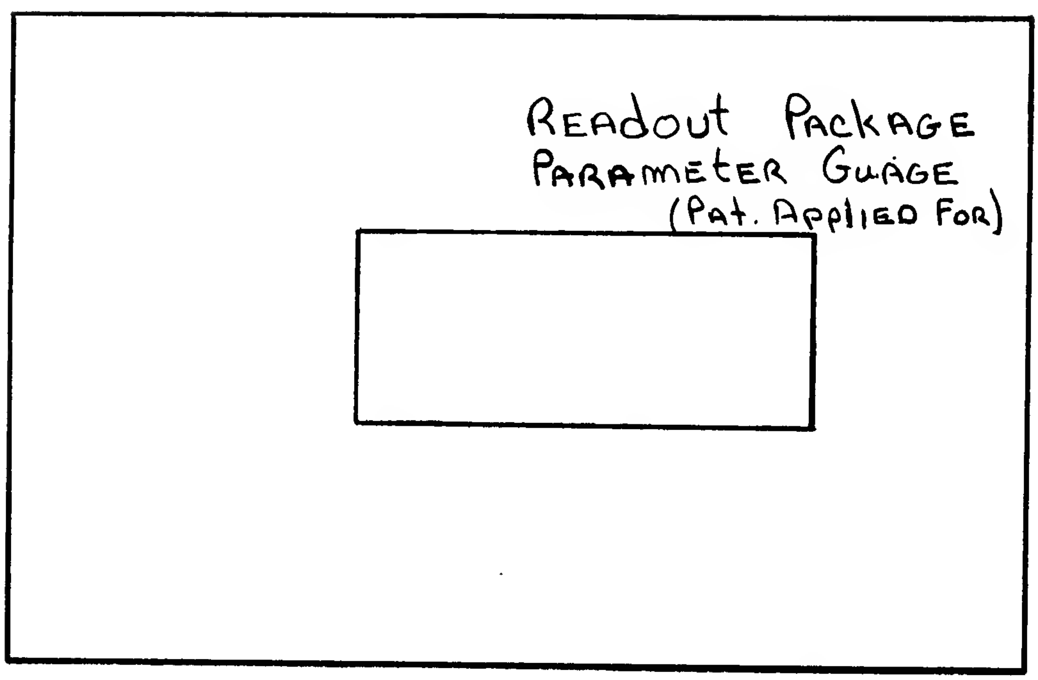
EXHIBIT "E"

Here is method of compacting idea on page 17:



The idler gears turn approximately 1.5 turns with respect to one another as the tape travels from one end to the other → so, the spring that loads them together must be fairly long to provide wind-up torque which is fairly constant throughout the entire cycle.

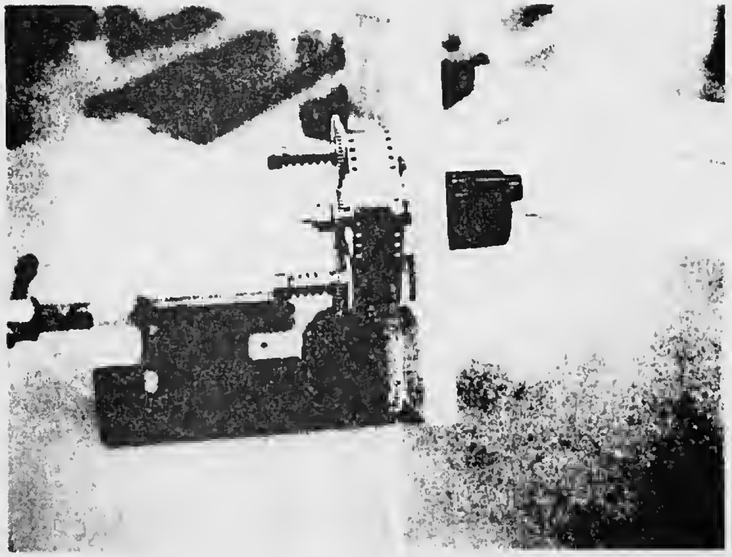
EXHIBIT F



Cardboard gauge showing read-out package parameters
selected by design group

11/14/64

EXHIBIT "G"



Same mechanism showing gear profile relationship. Springs on shoulder allen bolts just keep spools from riding up on gears.

→ This configuration tends to "solve" the varying diameter problem that exists as the spools transfer film. However, other stigmas are apparent as the knob is turned; ie: a fairly "tight" feeling as the film approaches either extreme due to the excessive windup of the relatively short length of spring.

Also, the readout area that confronts the eye of the operator tends to taper off from the central point of drive (the sprocket) which is not too desirable.

Therefore: (A) solve high spring tension problem
& - (B) attempt to flatten display area

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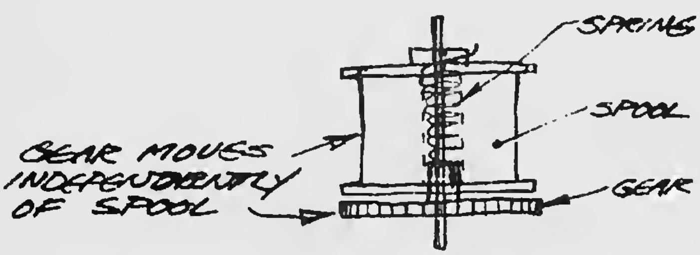
EXHIBIT "H"

In this setup - the spring tension is shared by both spools, each spool is loaded to a gear at its base thus:



The center gear, then, is just an idler which has a function of locking the gears at the base of each spool together, and thereby transmitting the torsional load of each spring's windup to the opposite spool.

→ The loading between storage spools, and ultimately the taking-up of the film slack is accomplished with minimum load strain on the film sprocket tooth and hole engagement.

The sprocket drive is off-set for more tooth engagement and this position allows an area which is unobstructed for a background and flat display.

EXHIBIT "I"

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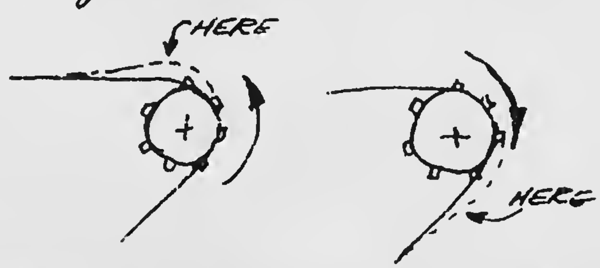
To reduce friction one of the idler spools is removed and the sprocket is put at that corner thus:

This reduced friction, but the starting moment in either direction tends to "bow" the film out at the corners



Increasing the natural radius of the film by using a larger sprockett helps to eliminate this situation; this conforms more ideally to the natural radius.

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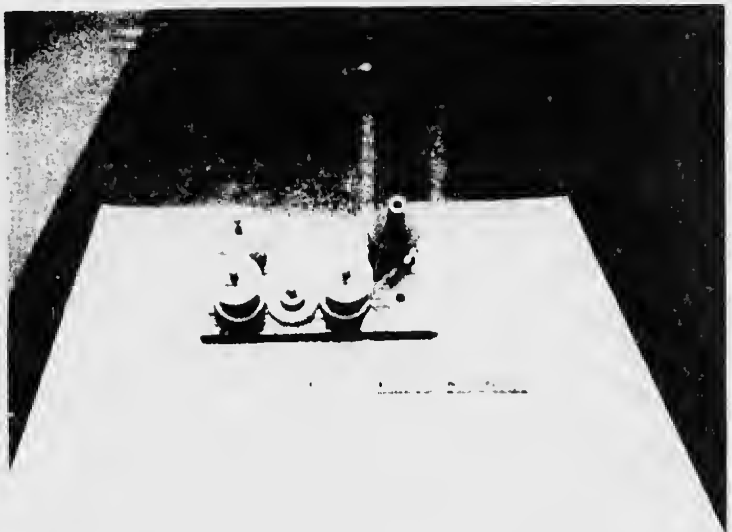
EXHIBIT "J"



Increasing the natural tendency to conform at the corners was further enhanced by the addition of a larger radius at the <u>other</u> corner.

→ Variations of this theme can be contrived to adapt to various needs and configurations — but the package is expanding in the meantime, which is undesirable.

Back to diminishing size, using the same spring loading feature from reel to reel and the larger sprocket for maximum possible tooth engagement.

→ <u>Problem</u>: no room for background?
— what about tangential drive with no possibility of tooth to tooth hoping?

EXHIBIT "K"

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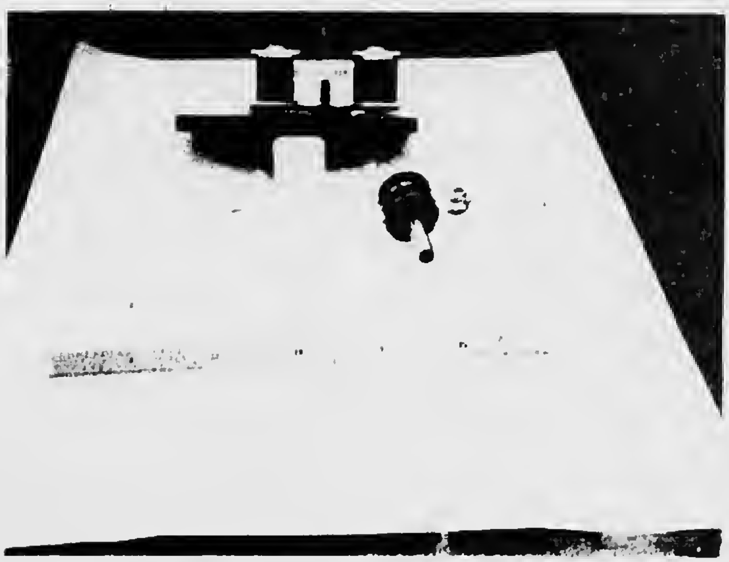
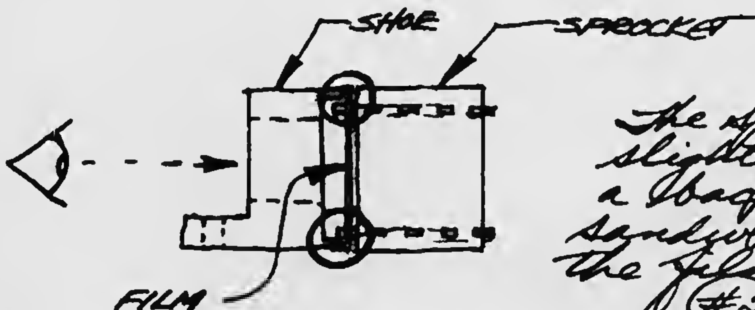


(2) .005 shim sprayed white w/ line glued in place

(1) The teflon shoe was made to describe an outline of sorts, of the bezel area, or viewing area. It also served as a holding member to make certain that the film did not ride off of the teeth: (areas circled in red)



The sprocket is undercut slightly to allow for a background to be sandwiched between the film and sprocket. (#2)

(3) Sprocket mounted on 1/4" shaft drilled to slip over 1/8" shaft with idler gear.

Completed assembly

Instructor's Note for Part (B)

This section of the case is the history of how the first stage of the read-out evolved. During the development, the design group became ~~diss~~atisfied with the idea they had picked. The idea was feasible. Should they continue with it or look for a new idea? This was the decision Tony had to make.

While reading this section of the case, the reader should see that a designer's first choice of an idea may not turn out to be the final choice, even though he has gone through the proper procedure of selecting it. The reader should see that there is a constant evaluation of the idea as it is developed and that at some time during the development, the idea may be scrapped and a new approach taken.

Possible student assignment:

If you were Tony, would you continue with the idea and develop it further? Why?

If you were to discontinue this idea, which other idea would you select or what would you do? Expalin.

The student who recognizes that the knowledge used in selecting the best idea from the advantage-disadvantage check list may or may not have been all correct or complete is on the right path to a solution. As this case works out, Tony found that some types of film did not have the disadvantages he had assumed for them.

(See next chapter.)